MEASUREMENT OF CAVITATION EROSIVE AGGRESSIVENESS BY MEANS OF STRUCTURE BORN NOISE

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Abstract

A measuring system was developed to estimate the cavitation erosive aggressiveness in a centrifugal pump during operation. The system is based on acoustical means. Acoustic pressure waves in water and vibrations of machine casings underlie several disturbances especially by changes of the transmission behaviour of the fluid during operation. Thus, an approach based on the structure born noise measured directly on the mechanical structure exposed to the cavitation was chosen to minimise this problems. The sensor, the amplifier and the signal processing and transmission devices have then to be placed within the rotating part of the machine. The measurements of the system have been compared with results of measurements using material specimen and coatings of soft copper. The physical relation between the acoustical event amplitudes detected by the system and the sizes of pits found on the specimen is discussed.

Nomenclature

c	: liquid velocity of sound	*(m / s)*
E_S	: acoustic energy	*(J)*
$E_{S,0}$	: minimum acoustic energy	*(J)*
$\hat{F}$	: force step amplitude	*(N)*
p	: pressure	*(Pa)*
R_{ref}	: scaling radius	*(m)*
t	: time	*(s)*
τ_P	: pulse duration	*(s)*
Δt	: width of gaussian pulse	*(s)*
ρ	: liquid density	*(m / s)*

Introduction

There are two main purposes of monitoring cavitation aggressiveness in turbomachinery: The first is the optimisation of maintenance intervals, the second is the active control of cavitation aggressiveness, e.g. by lowering rotational speed or by injection of air into the flow in front of the machine or directly into the cavitation zone respectively. As it is not economically reasonable to eliminate cavitation completely, the purpose of control also requires a reliable method of online quantification of cavitation aggressiveness in contrast to merely cavitation detection.

The methods of most importance are based on the noise generated by the cavitation. Especially high frequencies above some tens of kilohertz up to several megahertz are of interest as they are associated with bubble implosions which also act on the blades material. Beyond this, they are easy to distinguish from other noise sources in the machine. The noise is mostly measured in the liquid near the cavitation zone, on the casing of the machine or in the air in its vicinity. Two problems are associated to those methods. First, the noise may partly be generated by other sources like cavitating valves or bubble implosions far away from the exposed surface.

Second, the transmission behaviour of the vapour-liquid mixture may change with operation conditions. This is caused by a change of the volume of the cavitation zone or by a change of the amount of solved and dissolved gas in the liquid. Therefore, it is not always possible to attribute a change of noise to a change of cavitation aggressiveness. These problems can be minimised be measuring the structure born noise directly on the structure exposed to cavitation. Other sources have only small effect on this noise, changes in transmission behaviour are only caused by variation of the acoustic impedance of the surrounding liquid. This effect may be nearly excluded by a proper signal treatment. In the case of turbomachinery this method is more complex as the sensor and parts of the signal treatment facilities have to be placed within the rotating parts of the machine and signals have to be transmitted to the stationary part of the machine.

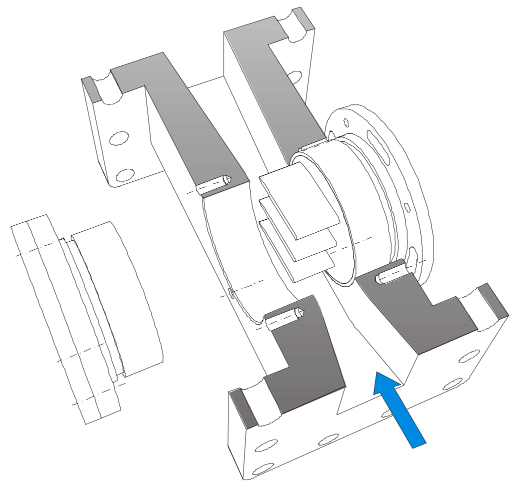

Figure 1. Hydrofoils cascade geometry - Cut through the test section

1 Experimental Set up

During development of the system, tests were carried out on a still impeller model (Figure 1). It consists of a cascade of three hydrofoils, located in a closed hydraulic loop. This takes into account, that in a real impeller noise is generated on several blades. The cross section of the channel is 30 by 100 mm. The angle of attack can be adjusted from 0 to 10 degrees. The cavitation number and the flow velocity can be varied. Maximum flow velocity is 18 m / s. On the non wetted side of the hydrofoils bearing plate, acceleration transducers can be mounted. To avoid gaps on the acoustic transmission way, the hydrofoils and the bearing plate are built from one single block. The cavitation conditions can be visually observed by a window on the opposite wall of the test section. Another set-up with the same geometry but hydrofoils with a soft copper surface can be used for reference measurements of the cavitation aggressiveness.
The second test facility is a single hydrofoil mounted in a 50 by 100 mm test section in the same rig and equipped with the possibility of air injection directly into the cavitation zone. In this case, the acoustic sensors are mounted on the base of the hydrofoil. Material specimen can be applied on this hydrofoil.
The third test facility is a centrifugal pump (Figure 2). It is also a part of a closed hydraulic loop. The impeller

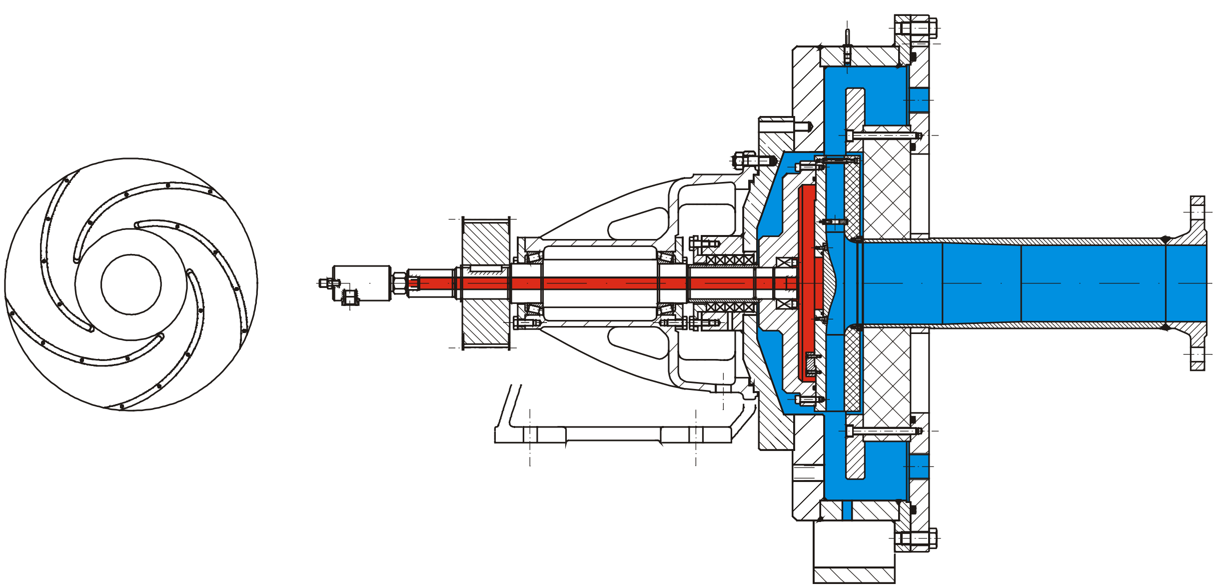

Figure 2. Test pump and plan view of the impeller

has a pure radial, two dimensional geometry. The casing is nearly of radial symmetry. Specific speed n_s equals 18, the diameter of the impeller equals 278 mm. The impeller is mounted on a bell which keeps the backside of the hub dry. The acoustic sensor is mounted on the hub. Also the amplifier is mounted here in order to obtain small cable lengths between sensor and amplifier. The amplifier can be switched to different amplification factors. Signal and power supply cables are led through the hollow shaft of the rotor. Signal treatment devices and telemetry are mounted on the end of the shaft.
The acceleration transducer is based on the piezoelectric effect (Ziegler M5W), cut off frequency is 2 MHz. The voltage amplifier used on the still configurations is commercial (EADQ AE Preamplifier V3202) with an amplification of 40 dB. The amplifier used in the rotor is especially designed for this purpose, amplification factor of about three.

2 Signal treatment

Structure born noise generated by cavitation has an event like character. It can be described more precisely as a kind of modulated random noise. An event is defined as a part of the signal in a time gate. The gate opens when the noise amplitude rises above a pre-set value. The amplitude rises quickly to a maximum and decreases more slowly afterwards. The gate closes with the last deflection greater than the discrimination level.
Each event may be viewed as the response of the mechanical and electrical structure to the implosion of a bubble near the structures surface. As the incitation is a pulse-like pressure wave of very short duration, many vibration modes of the structure are affected depending on the location of bubble implosion. The decrease time is determined by internal friction and emission into the surrounding liquid. The signal is well distinguishable from other noise sources. Cavitating components and ball bearings showed no significant influence.
There are several values which may be derived from an event like signal. The maximum amplitude is of most interest as it is directly related to the force acting on the surface and as there’s only small influence of the liquid. In any kind of liquid, air, water or a mixture of water and vapour, only few acoustic energy should be emitted during the relatively short rise time. This could be proved by numerical investigations using finite element methods.
There are only some tens or hundreds of cavitation events per second or even per minute depending on the discrimination level and the cavitation conditions, but the noise is measured up to several MHz. Hence the part of actually interesting information is very small. This makes the straightforward approach, transmission of the high frequent signal from the rotating system and processing afterwards seem uneconomic. Therefore, an analogue pre-processing device was developed, which extracts the information of interest but has also to be integrated within the rotating part of the machine.
This pre-processing device detects events if the noise exceeds a predefined trigger level. Afterwards the maximum voltage during an also predefined time window is held in a capacity and converted into a digital number by a microcontroller. Afterwards the capacity is cleared and ready for the next event. The digital number is Manchester coded and transmitted by a telemetric system to the stationary part of the machine. Electric power is also transmitted by the telemetry. Another microcontroller in the stationary part performs the Manchester decoding and transfers the number to a serial port of a personal computer.

3 Acoustical calibration

As the acceleration measured is treated as the answer of the mechanical structure on the inciting force of an imploding bubble, a calibration is necessary to estimate this force from the sensor signal. The calibration concerns the acoustical transmission behaviour of the structure, the coupling of structure and sensor, the sensor itself and the amplifier.
Due to the high frequencies measured, common methods which produce vibrations only in an audible range like hammer incitation or ball drop are not applicable. A very fast process is the breaking of a rod of glass or graphite like a pencil lead. The duration is in the range of a microsecond.
The set up for calibration consists of a pneumatic cylinder which is slowly loaded parallel to an accumulator. The pencil lead is mounted on the cylinder by a beam which also acts as a force sensor. During the slow rise of load, the force is measured continuously until the lead breaks on the surface of the structure to calibrate. Thus the incitation transient is known as a fast declining step with the height of the maximum force measured.

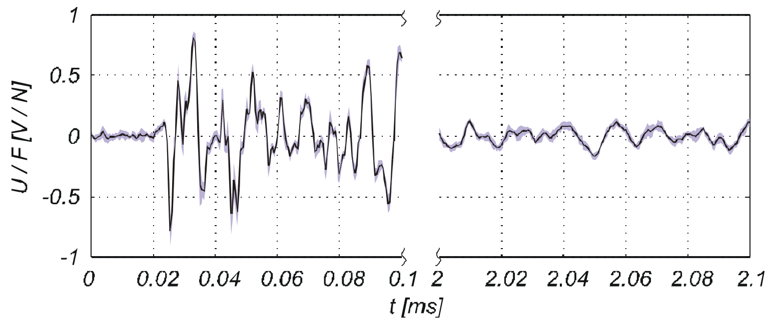

Figure .3. Calibration answers of several incitations of the cascade, mean transient (solid line) and standard deviation (shade).

The sensor answers are well reproducible if the location of incitation doesn't change and the sensor is not separated from the structure between the records (Figure 3). Thus, the change of incitation location under cavitation leads to an error in force estimation and the transmission way has to be calibrated again after every new coupling of the sensor.

4 Mechanisms of cavitation damage

The cavitation damage mechanism is still a matter of discussion. The dispute focuses on two possible causes:

- The spherical symmetry of the bubble implosion - which can't be expected in any case - is disturbed by a nearby wall in a defined manner. The disturbance can be explained by the Kelvin impulse that is impressed on the fluid during a bubble implosion far away from a wall (Blake et al. 1986). This impulse generates the so called microjet. This fluid jet moves from the opposite bubble wall towards the solid surface with velocities measured up several 100 m / s (Lauterborn et al. 1975, Vogel et al. 1989). Water hammer theory leads to high pressures capable to deform material (Lush 1983) but only short duration of stress.
- After the passing of the microjet the bubble decays to a number of microbubbles. These are exposed to the pressure wave generated by the microjet and therefore imploding more violently themselves emitting a high amplitude pressure wave, also capable to damage the solid material (Tomita et al. 1986).

In the past years pressure wave explanation prevailed (Fortes-Patella 1994, Philipp et al. 1998). Starting from this position, the reference measurement and the weighting of the acoustical measured force amplitudes is based on the supposition of a spherical wave emitted by the microbubbles.

5 Reference measure

The reference measure has to be obtained by a direct measuring method, i.e. by soft material specimen. There are two principles of using such specimen. First, one can observe just the earliest stages of cavitation damage, the formation of microscopic deformations, the so called pits. Second, one can observe the long term damage, i.e. material loss. These principles are well correlated (Simoneau 1995) and as the first provides more detailed information about the individual cavitation events, it is to prefer.

Determining a reference measure of cavitation aggressiveness has several purposes:

1. The capability of the integrated system to predict cavitation erosion can be evaluated
2. The measure can be used for calibration. Together with an acoustic calibration this should make the results independent from the type of machine.
3. Together with models of the damaging mechanisms, the relation of noise amplitudes and damage can be formulated physically. This is of value for testing the hypothesis, that each acoustical event results from a bubble implosion near a wall. Beyond this, the formulation should make the results independent from the material used for reference measurement.

For pitting experiments soft materials like pure copper or aluminium are used. Specimens are mounted flush with the surface of the exposed component. If a calibration is needed the view in local damage is insufficient. The entire surface under the cavitation zone has to be taken into account as the signal measured is also produced on the whole surface. Therefore the whole component has to be manufactured from or coated with the a soft material. In this work, the components where coated by electrolysis. Thickness of the coating is roughly 100 µm. The technique must be newly developed as the requirements for the surface are unusually. Surface roughness has

to be below 0.5 µm and the material has to be very soft, whereas industrially produced coatings preferably have to be hard.
The damage can be estimated by devices for three dimensional surface measurement like laser profilometers (Reboud et al. 1999) and interferometers, or by counting pits with the aid of a microscope (Lohrberg et al. 1999). If a very extended surface has to be examined, three dimensional methods are expensive and not well practicable. The surface affected by cavitation on the blades of the test pump equals up thousand square millimetres depending on the cavitation conditions. Hence, the damaged surfaces were photographed by microscope and CCD-Camera. Up to 800 images were taken per blade and fed to a digital image processing algorithm, that counted the pits and rated each pit by the radius of the cycle with equal expanse.
The further weighting of the pits goes back to a work performed by Fortes-Patella 1994. She provided empirical equations based on numerical investigations on spherical pressure waves of gaussian transient affecting solid materials. With the knowledge of the material properties, the peak height and the width Δt between the reversal points of the gaussian curve and the distance of the wave center from the wall, it is possible to predict radius and depth of the resulting pit. Conversely, if radius and depth of a pit and the duration of the responsible pulse is known, the energy of this pulse can be calculated.
As the surface analysis is only two-dimensional and the depth to radius ratio cannot be assumed as constant, its average value had to be derived from a calibration. A smaller specimen was analysed by both means, two-dimensionally by image processing and three-dimensionally by laser profilometry. The estimation of the pulse duration also needs the acoustical measurements as it appears in the following section. The material properties were assumed to equal the properties of metallurgically produced copper.
If the model is applied with the extensions described above a statistical relation between pit radius and the acoustical energy of causative pressure pulse can be formulated:

$$E_S = E_{S,0}\left(1+\frac{R}{R_{ref}}\right)^3 , \tag{1}$$

wherein $E_{S,0}$ is the minimum energy necessary to cause a pit and R_{ref} is a scaling radius.

6 Weighting of event amplitudes

If the pressure transient of the spherical wave is known, the pressure distribution on the solid surface can be derived by potential theory and mirroring the causative acoustic monopole on the surface. Integration of pressure transient over the surface leads to a step like force transient acting on the structure like the step used for acoustic calibration. The height $\hat{F}$ of this step is related with the energy of the acoustic wave by

$$E_S = \frac{\hat{F}^2}{\pi\rho c^3 \tau_P} . \tag{2}$$

Herein τ_P is the pulse width defined by

$$\tau_P = \frac{\left(\int_0^\infty p(t)dt\right)^2}{\int_0^\infty (p(t))^2\, dt} , \tag{3}$$

where the pressure transient $p(t)$ may be recorded at any radius greater than the bubble radius. If the wave has a gaussian transient, τ_P equals $\pi \cdot \Delta t / 4$. Unfortunately the value τ_P is usually not known. It depends on the initial bubble radius, the impellent pressure, bubble wall distance and contents of non condensable gas.
But if the cavitation aggressiveness is measured acoustically and by pit counting at the same operating conditions, the expected values of the energies estimated from both results can be adjusted by variation of the average pulse duration. This meets the requirement of system calibration and validation of noise generation assumptions as they were mentioned above at the same time. The assumption are validated if the resulting energies and pulse duration are in physically reasonable ranges.

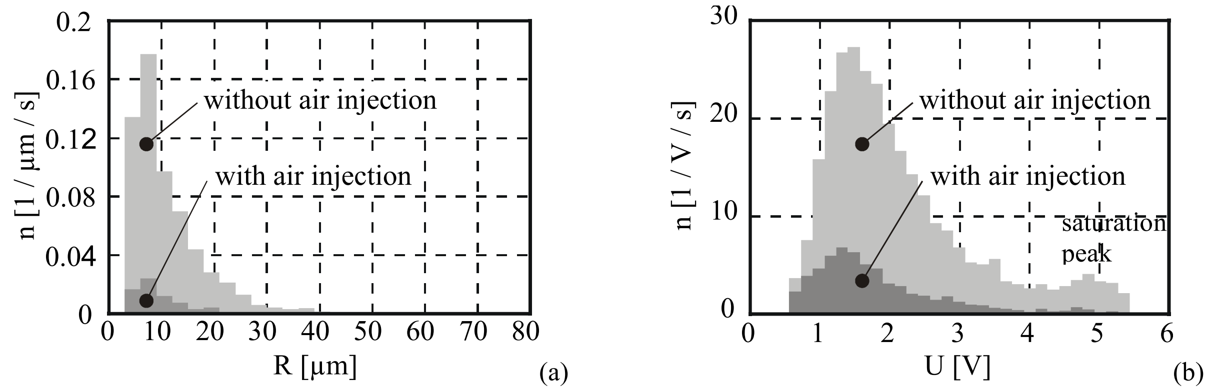

Figure 4. Pit (a) and event amplitude (b) histograms for different operating conditions

Thus, the sensor signal can be lead back to the fundamental values describing cavitation aggressiveness: number and energy of pressure waves emitted nearby the solid surface.

The weighted event amplitudes can be totalled to an integral measure of cavitation aggressiveness. If the sum is then normalised by the overall measuring time this value may be defined as the “implosive power” P_{Imp} of the cavitation.

7 Comparison of noise and cavitation damage

The first test case presented concerns the variation of cavitation aggressiveness by injecting air into the cavitation. The single hydrofoil was used for this test. The reference measurement of aggressiveness was carried out with the aid of a cylindrical specimen mounted flush to the surface of the hydrofoil. As the visual appearance of the cavitation doesn’t change by air injection it is probable that the damage reduction on the specimen mirrors the reduction on the whole surface. Thus this measurements can be compared with the acoustical measurements. The reference measurements were carried out by Böhm et al. 1998

Figure 4(a) shows the reduction in the pit radii histograms. The Number of pits as well as their average size is strongly reduced by the air. The pulse height histograms are affected in an analogous manner. The number of acoustical events as well as their average amplitude are reduced. Although the cavitation aggressiveness can’t be calculated in this case, its relative decrease can be quantified for both measurements. Implosive power drops to 8 % for the reference measurement and 12 % for the acoustical measurement. The lesser decrease of the acoustical amplitudes may partly be explained by the fact, that the signal processing is near saturation in the case of no aeration. This becomes visible in the peak on the right side of the histogram.

A second test was performed on the centrifugal pump (Figure 5). The relative flow rate was varied from 100 % to 108 %. The NPSH value was varied between 5 and 8 metres. For reference measurements, one blade of the

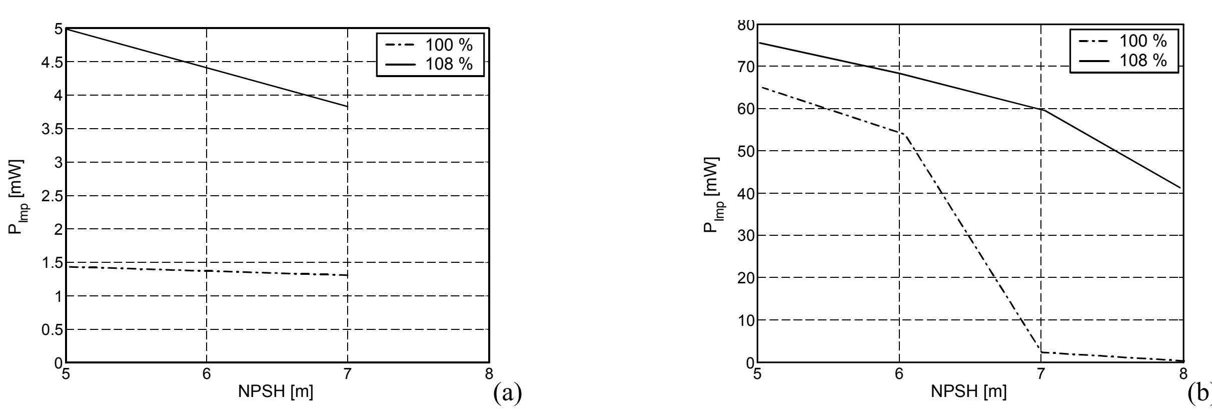

Figure 5. Implosive Power of cavitation as a function of operation conditions measured by pit counting (a) and by the integrated measurement system (b)

impeller was copper coated. Thus calibration could be carried out and implosive power could be determined.
Both proceedings show qualitatively same results. The acoustically measured power is substantially higher, because bubble implosions near the wall yet not near enough to cause a damage still incite the impeller strong enough to produce a detectable noise. Even if this effect is taken into account a deviation in tendency is left. An explanation may be difficulties in reproduction of the mechanical properties of the coating.
The average pulse duration τ_P estimated by calibration is about one microsecond. This in the range of earlier works results. The acoustical energies emitted are of order of some millijoule ($E_{S,0} = 0.13\ mJ$, $R_{ref} = 23\ \mu m$). As a vapour filled bubble of one millimetre radius situated in an ambient pressure of five bars has a potential energy of about two millijoule and as the greater part of this potential energy is transformed into acoustic energy during implosion, these values are physically reasonable.

8 Conclusions

An impeller integrated measurement system using the structure born noise of cavitation spreading in the exposed structure itself has to deal with less problems than acoustic systems using the fluid noise or vibrations of the machines casing. Transmission behaviour is less affected by fluid properties, other noise source have only few influence on the signal. Single bubble implosions near the surface can be separated as acoustic events.
The presented system has the capability of

- mirroring changes of cavitation aggressiveness due to air injection and other operational conditions,
- tracing back acoustic properties to the properties of the implosion of a bubble in physically comprehensible manner.

As the components of the system are comparatively inexpensive, the system can be used for research tasks as well as industrial application.

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